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Taras G. Pokhil and Roger B. Proksch

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A combined magneto-optic magnetic force microscope study of Co/Pd multilayer films

Taras G. Pokhil
Institute for Rock Magnetism, University of Minnesota, Minneapolis, Minnesota 55455

Roger B. Proksch
Magnetic Microscopy Center, University of Minnesota, Minneapolis, Minnesota 55455 and Department of Physics, St. Olaf College, Northfield, Minnesota 55057

We have combined a magnetic force/atomic force microscope (MFM/AFM) with a magneto-optic (MO) microscope. This instrument combines the high spatial resolution of the MFM/AFM and its capability to correlate magnetic structure with the structure of the sample surface with the real-time imaging capabilities and large field of view of the MO microscope. Our MO/MFM setup is based on the Nanoscope III Multimode™ MFM/AFM (Digital Instruments, Santa Barbara, CA). Currently, the spatial resolution of the MO microscope is about 3 μm and polarization sensitivity is on the order of 0.5°. Using this instrument, we observed domain structures in Co/Pd multilayer films. We found that in a film with 20 Co/Pd layer pairs and 16 nm total thickness, nucleation of domains during sample remagnetizations occurs repeatedly in the same points, and that displacement of domain walls is unidirectional. The high topographic resolution of the AFM allowed us to show that domains nucleate at small defects on the sample surface. The depth of the defects is 1–2 nm, they are 20–30 nm wide and up to 500 nm long. The unidirectional displacement of the domain walls was found to correlate with the anisotropic structure of the sample surface.
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I. INTRODUCTION

Magneto-optic (MO) microscopy is an optical technique based on using magnetooptic Kerr and Faraday effects. It allows observation of nucleation and displacement of domain walls with high time resolution.[1,2] The spatial resolution of a regular MO microscope is limited by the optical resolution limit (~1 μm). Magnetic force microscopy is a technique sensitive to the magnetic stray field above the surface of magnetic material.[3] The resolution of the MFM can be up to 10 nm.[4] The combination of the real-time imaging capability of the MO microscope with high spatial resolution of the MFM allows a study of the microscopic behavior of domain walls in dynamic processes such as domain wall displacements. In addition, since the MO microscope is sensitive to the sample magnetization and the MFM is sensitive to the magnetic field from the sample, information from the two techniques is complimentary.

In this article we describe combined magneto-optic/magnetic force microscope (MO/MFM) and present the results obtained with the microscope on nucleation and displacement of domain walls in Co/Pd multilayer films.

II. EXPERIMENTAL SETUP

Our MO/MFM setup is based on straightforward modifications of our Nanoscope III Multimode™ magnetic force/atomic force microscope (Digital Instruments, Santa Barbara, CA). We used the Nikon optical microscope with long working distance objective for the MO observation of domains. It allows the observation of the MFM cantilever positioned over the sample, from a distance 4 cm. We modified the optical scheme of the microscope to make it possible to observe the samples in polarized light (Fig. 1). We included two film polarizers (parts 6, 9 in Fig. 1) in the optical scheme of the microscope and put them close to the semitransparent mirror (5, Fig. 1). This arrangement allows us to observe domain structures using polar Kerr effect. The spatial resolution of the MO microscope is about 3 μm and polarization sensitivity is roughly 0.5°.

The MFM operates in the ''tapping/lift'' scanning mode,[5,6] which combines constant interaction and constant height modes, to separate topographic and magnetic signals. The magnetic images were obtained by detecting MFM tip oscillation amplitude in constant height mode. The scanned probes were batch fabricated Si cantilevers with pyramidal tips coated with a CoCr film alloy.[7] All MFM data shown in

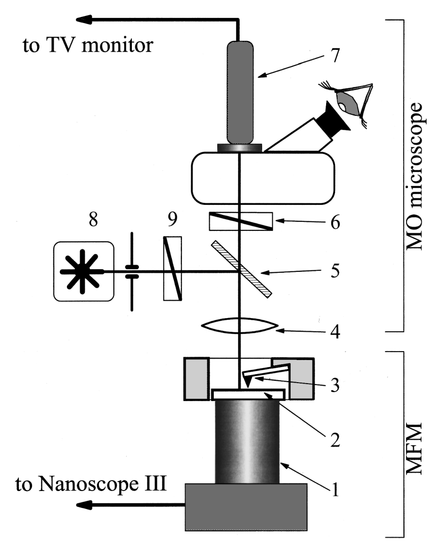

FIG. 1. Design of our MO/MFM microscope: (1) MFM scanner, (2) sample, (3) MFM tip, (4) objective, (5) semitransparent mirror, (6) polarizer I, (7) CCD camera, (8) lamp, (9) polarizer II.

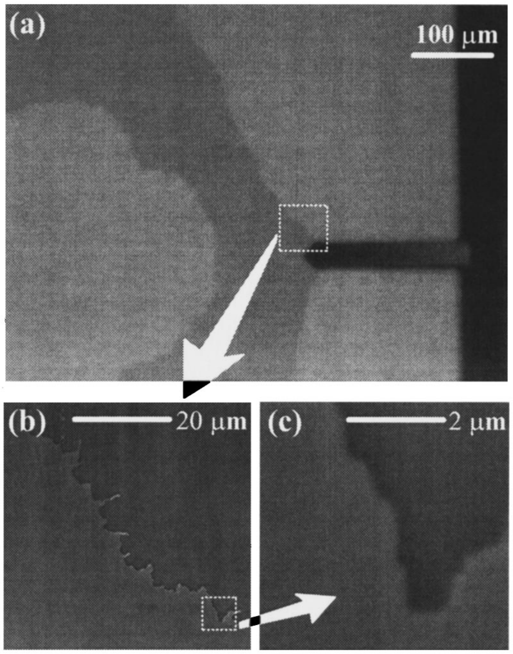

FIG. 2. Images of the domains in 8-nm-thick Co/Pd multilayer film obtained with the magneto-optic/magnetic force microscope: (a) MOKE image of the domains showing location of the MFM cantilever; (b) MFM image of the area outlined in (a); (c) high resolution MFM image of the domain boundary in the area outlined in (b).

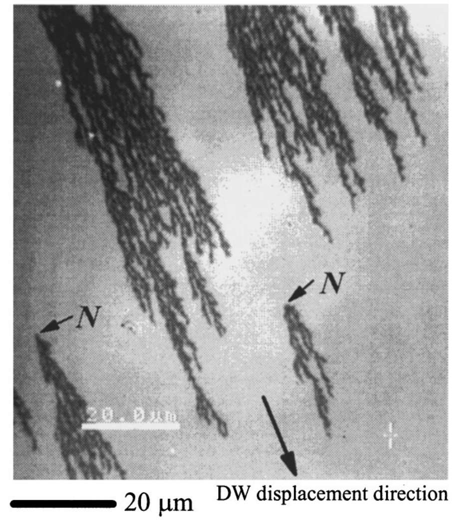

FIG. 3. MOKE image of the anisotropic domains in 16-nm-thick Co/Pd multilayer film. Points of domains nucleation are marked with N, and the direction of domain walls displacement is shown with the arrow.

this article were collected with the tip magnetized approximately perpendicular to the sample surface (z direction), making the MFM mostly sensitive to the second derivative of the z component of sample stray field. All MFM images presented in this article were obtained with tip sample separation of 30–50 nm and tip oscillation amplitude of 20–30 nm. The drive frequency of cantilever was chosen above the resonance frequency of the cantilever near the point of maximum gradient of the cantilever resonance curve.

The sample magneto-optic Kerr effect (MOKE) and MFM images of the domains in 8-nm-thick Co/Pd multilayer film having 10 pairs of layers obtained with the MO/MFM setup are presented in Fig. 2. Figure 2(a) shows the MOKE image of the domains and the location of the MFM cantilever. The magnified images of the same domain obtained with the MFM are shown in Figs. 2(b) and 2(c).

III. NUCLEATION AND UNIDIRECTIONAL DISPLACEMENT OF DOMAIN WALLS

In this work, we used the MO/MFM to study domain structures in Co/Pd multilayer films. The films were sputtered onto Si (111) substrates.[8] The thickness of Co and Pd layers were about 1.5 and 6.5 Å, respectively. The studied samples had 10 and 20 Co/Pd pairs of layers and total thickness of 8 and 16 nm, respectively. The coercive force of the samples was about 1 kOe for 8-nm-thick film and about 1.5 kOe for 16-nm-thick film. Domains in the 8 nm film were solid and had a shape close to bubble domains (see Fig. 2). In the 16 nm sample mazelike domains were observed (see Fig. 3).

We used the MO microscope to observe the real time nucleation of domains and displacement of domain walls in an external magnetic field near the coercive point. One interesting observation was that domains seemed to nucleate at the same points on the sample surface during different magnetization cycles. The distance between the points of domain nucleation under the field approaching the coercive force was 20–50 μm. Another interesting observation was that the displacement of domain walls was anisotropic in the 16-nm-thick film. The domain walls moved primarily in one direction, forming dendritic structures. This is illustrated in the MOKE image shown in Fig. 3. Although the spatial resolution of the MO microscope was insufficient to explain these two observations, the MO position the MFM cantilever over the points of interest for higher resolution magnetic and topographic imaging.

High resolution MFM image of the area of domain nucleation in 16-nm-thick film and AFM image of the film surface topography of the same area are shown in Fig. 4. It is seen in the images that the domain is nucleated at a small elongated defect on the film surface. The depth of the defect is 1–2 nm, it is 20–30 nm wide, and about 500 nm long. All domains that we studied with the MFM/AFM in the film were nucleated at similar defects. Therefore, even small de-

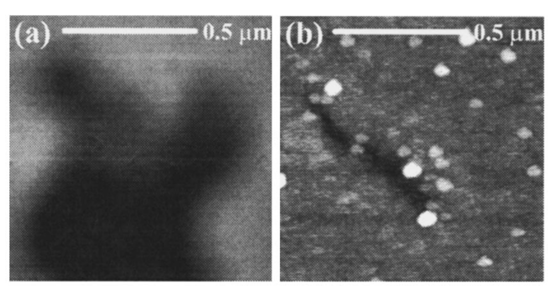

FIG. 4. High resolution (a) MFM and (b) AFM images of the area of domain nucleation in 16-nm-thick Co/Pd multilayer film.

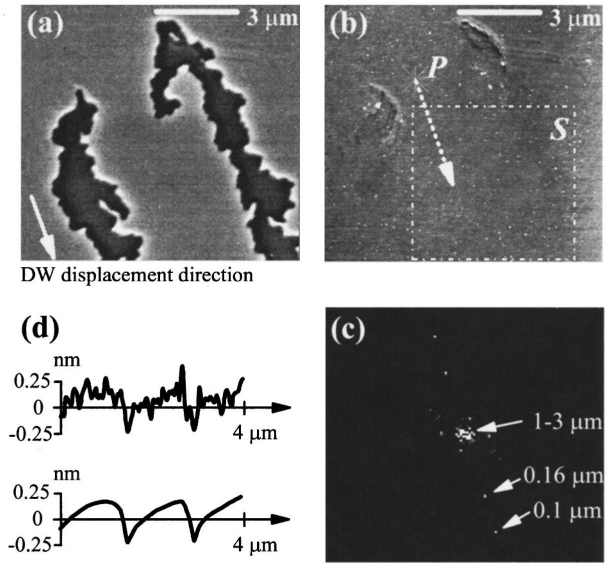

FIG. 5. (a) MFM image of the domains in 16-nm-thick Co/Pd multilayer film; (b) AFM image of the same area of the film surface; (c) 2D Fourier spectrum of the surface area S outlined in (b); (d) AFM profile of the surface and smoothened AFM profile taken along the line P shown in (b).

fects with the depth 10%–20% of the film thickness act as ''weak'' points in which the probability of domain nucleation is higher than in surrounding areas of the film. The domain nucleation process under external field approaching coercive force of the films is a thermally activated process,[9] thus, a small difference in energies of domain nucleation in different points of the film can result in high difference in probabilities of the nucleation.

As we mentioned above we observed unidirectional displacement of domain walls in 16-nm-thick Co/Pd multilayer film. We found that the structure of the film surface is anisotropic in the plane of the surface, and that anisotropy of the surface correlates with the direction of domain walls displacement (Fig. 5). The roughness of the surface areas between visible defects is less than 0.5 nm, so it is hard to see a well pronounced anisotropic surface structure in the AFM image [Fig. 5(b)]. However, the two-dimensional Fourier spectrum of the surface image [Fig. 5(d)] shows that the surface has an anisotropic structure. The points in the spectrum corresponding to the wavelength 0.1 and 0.16 μm are located at the line which is parallel to the direction of the displacement of domain walls [Fig. 5(a)]. In all other directions the spectrum contains points corresponding to just the longer wavelengths (1–3 μm). The AFM profile of the surface [Fig. 5(c)] taken in the direction parallel to the displacement of the domain walls shows that the surface has a unidirectional anisotropy. The local slope of the surface in the direction of domain wall displacement is lower than in the opposite direction. The areas of the high slope correspond to the wavelength 0.1–0.2 μm in the two-dimensional Fourier spectrum, and areas of the low slope correspond to 1–3 μm. As was shown earlier,[10] such surface structure results in the unidirectional displacement of domain walls.

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